

The Role of Dentin in Tooth Fracture

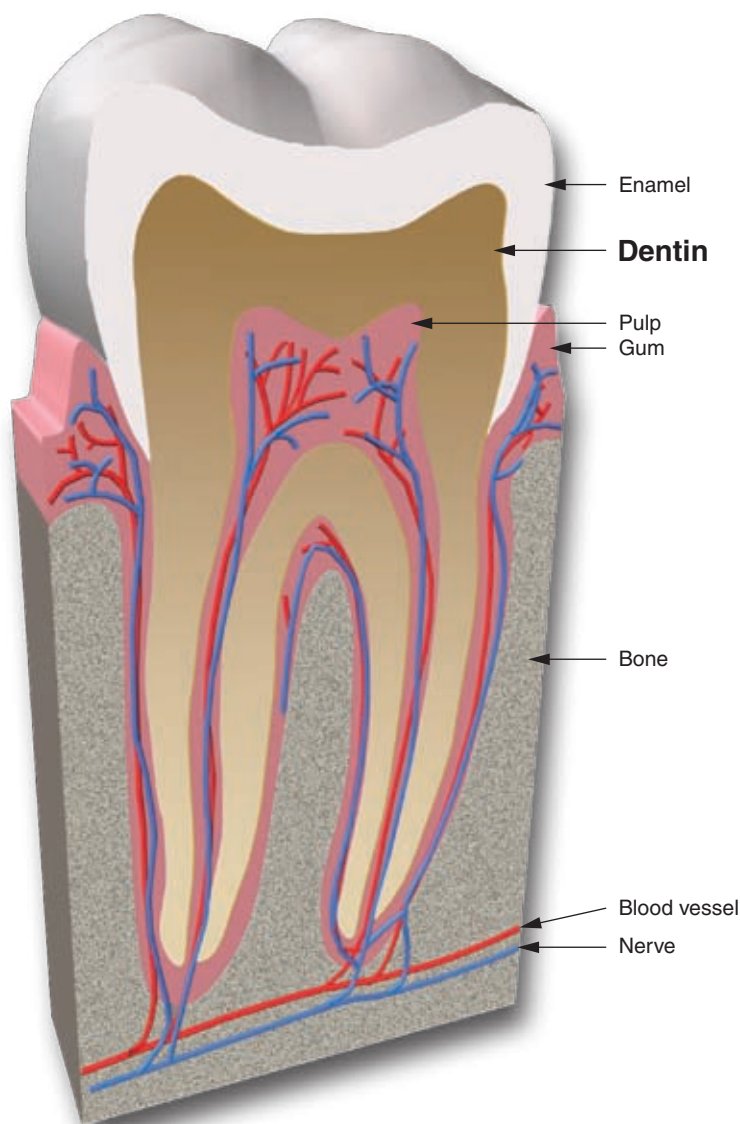
OUR parents and grandparents are among the first generations to reasonably expect to retain their teeth into old age. Improvements in diet and dental care over the past 50 years have reduced tooth loss from decay and gum disease. Today, a greater percentage of aged teeth fail from fracture. However, why older teeth break is unclear. Many scientists have suggested that restorative procedures, such as root canals or dental fillings, concentrate stress and make teeth vulnerable to fracture. Others have proposed that everyday tooth wear—brushing or grinding, for example—leaves cracks that later grow until a tooth fails.

A team of scientists from Lawrence Livermore and Lawrence Berkeley national laboratories and the University of California at San Francisco (UCSF) has observed that the hard tissue inside the tooth, called dentin, becomes brittle with age. Livermore physicist John Kinney, who is codirector of a multicampus project funded by the National Institutes of Health to study tooth fracture, says, “Embrittlement appears to occur as a natural aging process, even in the absence of decay or restorative procedures.” Although the cause of this embrittlement is still unknown, recent evidence suggests that age-related changes at the molecular level may be responsible.

Sandwiched between the hard exterior cap of enamel and the central tooth chamber, dentin is the major structural component of the tooth. Softer than enamel, this tissue is part mineral (hydroxyapatite crystallites), part organic material (primarily collagen), and part fluid. At the microscopic level, dentin is a network of mineral and collagen through which tubes, called dentinal tubules, radiate outward from the central chamber to the enamel above. Surrounding each tubule is a mineral buildup called the cuff. These fluid-filled tubules measure just a couple of micrometers in diameter and are permeable, allowing them to transfer the sensation of hot or cold foods to the pulp nerves or trigger tooth pain.

Understanding Dentin’s Basic Behavior

Traditional mechanical tests to measure the hardness and stiffness of dentin typically have resulted in large discrepancies among results, making it challenging for scientists to establish the tissue’s basic mechanical behavior or to explore the effects of age on tooth strength. However, using a range of diagnostics at the Livermore and Berkeley laboratories, Kinney and his



collaborators narrowed the uncertainties in dentin’s mechanical properties.

According to Kinney, some of the biggest advances in developing a more precise picture of how teeth fail have been made through the collaborative work of Robert Ritchie’s group at Lawrence Berkeley. Ritchie’s group measured fracture toughness—the ability of a material containing a crack to resist fracture—in tooth specimens using mechanical techniques developed for research on ceramics and metals. The researchers initiated cracks in samples of dentin, put the samples under stress, and then watched the cracks grow using a scanning electron microscope (SEM).

The three-dimensional SEM images revealed that once a crack begins, some of the tubule cuffs near the advancing edge of the crack, known as the crack tip, develop cracks and relieve some stress. Uncracked “bridges” in the collagen network between the cracked cuffs act like steel rods in reinforced concrete. They hold the tooth together by limiting the crack opening and absorbing some of the applied load that would otherwise

further crack propagation. Ritchie describes this behavior as an “extrinsic toughening mechanism similar to what is seen in many engineered materials.”

The Berkeley group has also answered a long-standing question in dentin research—whether crack growth at low loads requires cyclic stressing (that is, alternating cycles of loading and unloading that mimic an activity such as chewing). Their research proved that cracks in dentin only grow if the load is cycled, a process known as fatigue. When dentin is held at constant stress, cracks become blunted, increasing the required stress for the crack to advance. Cycling the load permits the crack tip to alternately sharpen and blunt, advancing the crack.

Properties Change with Age

Thanks in large part to the team of Livermore, Berkeley, and UCSF researchers, the properties and microstructure of young, healthy dentin are now well understood and can be used as a baseline for characterizing how dentin ages. As teeth age, the tubules begin to fill with mineral deposits, starting at the root end and working upward. This phenomenon is known as transparency because the mineral deposits prevent the tubules from scattering light. As part of the National Institutes of Health study, Kinney’s team focused on comparing the structure and micromechanical properties of younger dentin with older, more transparent dentin. This study required highly specialized analytical tools, including

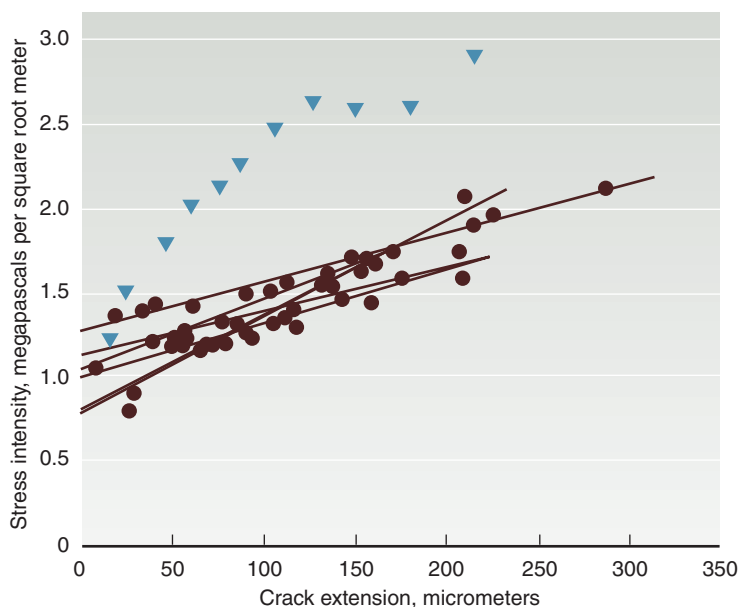
small-angle x-ray scattering at the Stanford Synchrotron Radiation Laboratory; resonant ultrasound spectroscopy and atomic force microscopy (AFM) at UCSF; and transmission electron microscopy at Lawrence Berkeley. The goal was to explore whether aging produced detectable changes in dentin’s structure and properties.

The results of the aging study indicated that subtle changes occur in the size and shape of the mineral crystallites. However, no differences were observed in the elastic properties of young and old dentin measured with resonant ultrasound spectroscopy. These results were confirmed by nanoscale AFM indentation studies in the lab of Bill and Sally Marshall at UCSF. Initially, Kinney’s team concluded that aged dentin was most likely as robust as young dentin. However, results from fracture studies at Lawrence Berkeley indicated that this early view was too optimistic.

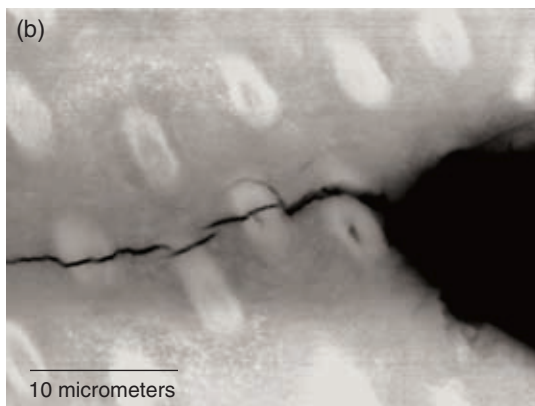
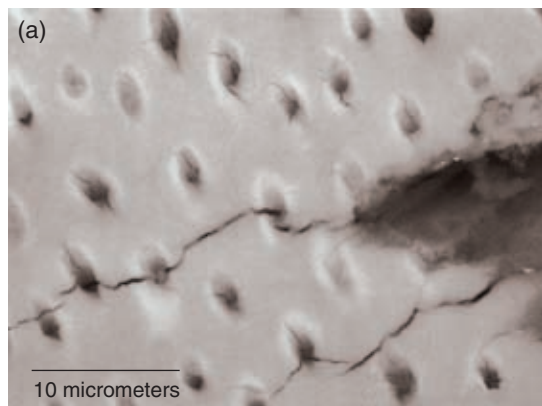
Mechanical studies showed that older dentin has distinctive fracture and fatigue behavior. Of greatest significance was the finding that dentin becomes brittle with age. When young dentin is stressed, it visibly yields and deforms prior to breaking. However, the collaborators found older dentin does not yield before failing. At a microscopic level, older teeth appear to form far fewer microcracks in front of a crack. As a result, less of the strain energy is relieved, and virtually no bridges are produced. Fracture toughness in aged dentin measured about 20 percent lower than in young dentin. (See the figure on p. 19.) The team also studied how likely teeth were to crack from repeated stress and found that older dentin displayed a lower fatigue resistance, especially when subjected to higher stresses.

The culprit for increased brittleness in older dentin initially appeared to be the tubules, which, when filled, become stiffer. However, the team found that aged dentin does not create stress-relieving microcracks and bridges, regardless of whether the nearby tubules are open or plugged. Based on observations of fracture behavior on both visible and microscopic scales, further research advances require study at the molecular level to understand what is causing age-related dentin embrittlement.

Current research at the molecular scale is focused on the mineralized collagen network, the component of dentin that provides teeth with elasticity and strength. Recent work by Kurt Koester, one of Ritchie’s graduate students, indicates that crack-tip blunting, known to occur in young dentin, is greatly reduced or absent in aged dentin. Crack-tip blunting requires molecular motion in the collagen, so the fact that aged dentin does not experience blunting indicates something in the aging process is affecting collagen mobility. Kinney says, “At that tiny scale, we observed the robust tissue turning into a brittle substance as it aged.” He suspects that either the collagen molecules increase in cross-linking density or dry out as the collagen ages, or the mineral nanocrystals in the collagen change in their shape, size, or orientation over time and somehow prevent the collagen from



This graph captures the macroscopic-level behavior of young (blue) and aged (brown) dentin in fracture experiments. Once a crack was induced in dental tissue, higher levels of stress had to be exerted on the younger dentin than on the older dentin for the crack to grow.



Scanning electron microscope images show how in (a) young dentin, the dentinal tubules form microcracks in response to an approaching crack, relieving some of the stress that would otherwise contribute to crack propagation. (b) Aged dentin has more mineralization in the tubules and a brittle intertubule network of collagen, so it does not form as many microcracks or inhibit the crack's progress.

moving. Either process, or both processes, could be causing the crack tip to remain sharp in aging dentin.

Future Investigations

Although evidence is mounting that age-related changes on a nanometer scale may lead to the deterioration of fracture properties of the tooth as a whole, more research is necessary to determine precisely what is happening. To date, physical measurements made of dentin's mechanical properties have been limited to the tissue's response across multiple length scales. The team plans to narrow its focus by using small-angle x-ray scattering to measure the strain in individual collagen fibers and the size and orientation of nanocrystals in young and aged dentin. Because fillings, crowns, bridges, and other dental repairs must bond to dentin, "knowing more precisely how dentin changes with age will also help advance restorative dentistry treatment methods," says Sally Marshall.

For Kinney, an important outcome of the dentin studies is the insight it brings to his bone fracture investigations. (See *S&TR*,

September 2006, pp. 20–22.) Because dentin is nearly identical in composition to bone on the nanoscale, the study of aged teeth may reveal why aging bones often become fragile.

Using techniques traditionally applied to study engineering materials, researchers are approaching a better understanding of difficult-to-study biological materials on several scales. Although stopping the effects of time may be impossible, the studies on dentin, and aging tissue in general, may increase awareness on the effects of aging and improve treatment for both tooth and bone disease.

—Rose Hansen

Key Words: atomic force microscopy (AFM), collagen, dentin, dentinal tubules, fracture toughness, resonant ultrasound spectroscopy, scanning electron microscope (SEM), transmission electron microscopy.

For further information contact John Kinney (925) 422-6669 (jhkinney@pacbell.net).